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COLD GAS ANALYSIS OF A WASTE-GAS INCINERATOR TO ENHANCE MIXING CAPABILITIES USING CFD

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ABSTRACT

Reducing the combustion length, improving the flame stability, generating sufficient vortical recirculation zones, and extending the durability of furnace insulation are some reasons to target swirling flow in combustion chambers with sufficient swirl characteristics. These reasons aim to increase the species residence time and improve the mixing quality in the related combustion chambers. As is known, burning the waste-gas material in incinerators can produce toxic pollutants. Nevertheless, one main objective in incineration combustor is to improve the flow mixing characteristics. Our concern in this paper is to improve the mixing characteristics of one available incinerator with some unsuitable pollution using the CFD simulation. We study the flow patterns and analyze the mixing quality to monitor the influence of waste-gas inlet cross-sections and its position into the incinerator chamber. The degree of mixing is analyzed using the standard deviation parameter, which determines the homogeneity of the fuel mixture fraction in the incinerator chamber. The improvement of mixing characteristics and increasing the residence time in the incinerator are two important factors, which are suitably elaborated and discussed in this paper. The mixing study is provided for cold gas assumption.

INTRODUCTION

In this paper, we address the analysis of mixing in an industrial hydrocarbon-based waste gas incinerator. The waste gases are produced in some industrial units; however, they cannot be released in ambient due to their high pollution. So, it is required to re-burn or incinerate these by-products to eliminate their pollutants. Since the waste gas entering the incinerator itself is a low-grade fuel, it can further contribute to a better incineration process and self-burning. The measurements from the stack of this incinerator have shown that the concentration of pollutants like NO_x and CO would be considerably high. So, it needs immediate attention to reduce the imposed pollutants sufficiently low. The observations and simulations show that the shape of flame would be asymmetric despite a symmetrical configuration for the incinerator and burner. These problems, i.e., high pollutant concentrations on one hand and the asymmetric shape of flame on the other hand, promoted the industry to find some remedies to rectify them. As a side effect, an asymmetric flame would expose the incinerator wall at high temperature magnitudes, which is not consistent with its design considerations.

Past investigations show that the flow swirling can stabilize the flames with complicated flow patterns [1-9]. Some advantages of using swirling flows in combustion systems are as follows [5]:

1. Reducing the combustion length by producing higher rates of entrainment of ambient fluid.
2. Providing fast mixing close to the exit nozzle and on the boundaries of the recirculation zones.
3. Improving the flame stability as a result of vortical structure in the recirculation zones.
4. Minimizing the flame impingement on the furnace wall, which can reduce the maintenance cost and extend the life for the furnace units.

Mixing is known as a general remedy to improve the basic characteristics of an incinerator. We also consider this important target and try to improve it in our incinerator using three-dimensional simulation of the incinerator. This permits to study the flow patterns and analyse the turbulence intensity parameter, whose suitable control can affect the quality of incinerating the related waste gas. The mixing level can be qualified using the standard deviation parameter, which determines the homogeneity of fuel mixture fraction in the solution domain. Generally, the flow swirl in incinerator can both decrease the chemical reaction zone and increase the flame blow-off limits to infinity. Choi et al. [10] proposed a scheme to quantify the degree of mixing. Kim et al. [11] applied this scheme to evaluate the design of a 2D incinerator. They showed that by means of flow characteristics, such as the path of jet entering into the incinerator, one can control the recirculation zone and its mixing degrees. In other words, the mixing is affected by the variation of momentum flux rate from the waste gas jets entering as the main stream of incinerator into the incinerator. Ryu and Choi [12] showed that changing the angle and distance of entering jets from a direction parallel to the axis of incinerator, which is parallel to the flame elongation, would have positive effects on the mixing quality and pollution control.

There are a few ideas to improve the quality of incineration in an incinerator considering the two waste-gas and fuel-air jet streams into the incinerator [13-15]:

1. A wider distribution of waste gas patterns in the incinerator, which can subsequently improve the waste gas incineration effectively.
2. Choosing suitable number, location, and the mass flow rate magnitudes for the waste gas jets entering into the incinerator.
3. Choosing suitable entrance angle with respect to the flame and the wall of incinerator for both jets streams.
4. Choosing suitable cross sections for the entering jets; preferably a staggered arrangement.

The main purpose of this paper is to analyse the mixing quality using different arrangements of entering jets, which can in turn improve the mixing quality and increase the residence time for the species appearing in the incinerator.

NOMENCLATURE

f	[-]	Mixture fraction
$\overline{f}$	[-]	Mean mixture fraction
f'	[-]	Mean mixture fraction fluctuations
$\overline{f'^2}$	[-]	Mixture fraction variance
g	[m/s^2]	Gravitational acceleration
k	[m^2/s^2]	Turbulence kinetic energy
N	[-]	Total number of mesh cells located on a plane
P	[kg/m.s^3]	Production of turbulence
p	[N/m^2]	Pressure
$\overline{p}$	[N/m^2]	Mean pressure
R	[kg/m.s^2]	Reynolds stress
T	[K]	Temperature
t	[s]	Time
$u(x,t)$	[m/s]	Velocity as a function of space and time
$\overline{u(x,t)}$	[m/s]	Time averaged velocity component
$u'(x,t)$	[m/s]	Fluctuating velocity component
u^+	[-]	Scalar velocity
u_τ	[m/s]	Friction velocity
$\vec{v}$	[m/s]	Velocity component in y direction
y^+	[-]	Scalar coordinate (local wall Reynolds number)

Special characters

Z	[-]	Mass fraction
τ	[N/m^2]	Shear stress
σ	[-]	Mixture fraction variance
ρ	[kg/m^3]	Density
μ	[Pa.s]	Dynamic viscosity
ε	[m^2/s^3]	Dissipation rate of turbulence kinetic energy
δ	[m]	Boundary layer thickness
∇	[-]	Gradient operator
$\nabla.$	[-]	Divergence operator
$\langle\ \rangle$	[-]	Time-averaging operator

Subscripts

fuel	Stream originates from the fuel nozzle
sec	Stream originates from the secondary feed to the combustion chamber
ox	Stream originates from the oxidizer conduit
i	ith element
i	Component of a variable in x direction
j	Component of a variable in y direction
w	Wall
t	Related to turbulence

GOVERNING EQUATIONS

Mixture Fraction

In case of non-premixed combustion, fuel and oxidizer enter the reaction zone through two separate conduits. Mixture fraction is a good parameter to monitor the combustion process because it makes it possible to trace the weight of burned and unburned species in the incinerator. Mixture fraction can be regarded as a conservative scalar parameter. Using this parameter, we can reduce a reacting flow problem to a simple non-reacting mixing flow problem. This eliminates the need for accounting the nonlinear mean rate equations in our simulations. The mixture fraction is defined as [13]:

$$f = \frac{Z_i - Z_{i,ox}}{Z_{i,fuel} - Z_{i,ox}} \tag{1}$$

where Z is the mass fraction of the element i and the subscripts ox and $fuel$ denote the oxidizer and fuel streams, respectively. Modeling of non-premixed flames needs the solution of transport equations for one or two conservable scalars, of which one is the mixture fraction. In this way, the equations do not need to be solved for each species individually because the species concentrations can be extracted from the predicted mass fraction fields instead. Having this in hand, the relation between temperature, density, and mole fraction of the species can be readily obtained from the fuel mixture fraction. Figures 1-3 show mole fraction of species, mean density and temperature of mixture in terms of mixture fraction, respectively. In the rest of this study, the thermochemistry calculations and the interaction between chemistry and turbulence are accomplished using suitable probability density function.

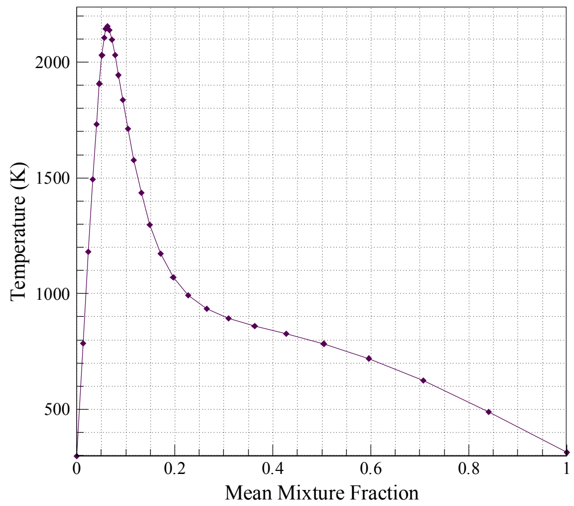

Figure 1 Temperature versus fuel mixture fraction

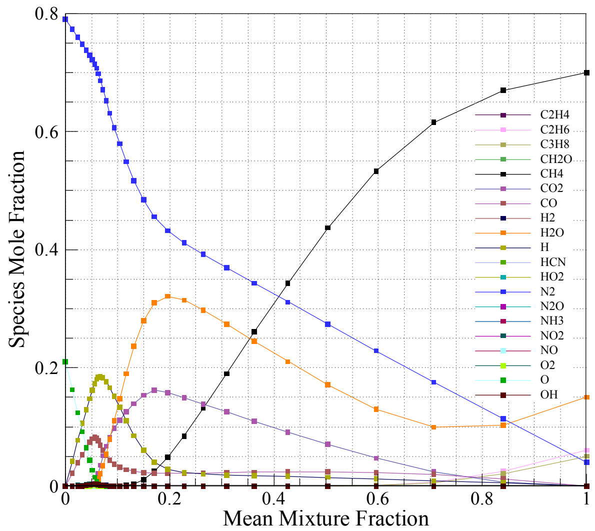

Figure 2 Mole fraction of species versus fuel mixture fraction

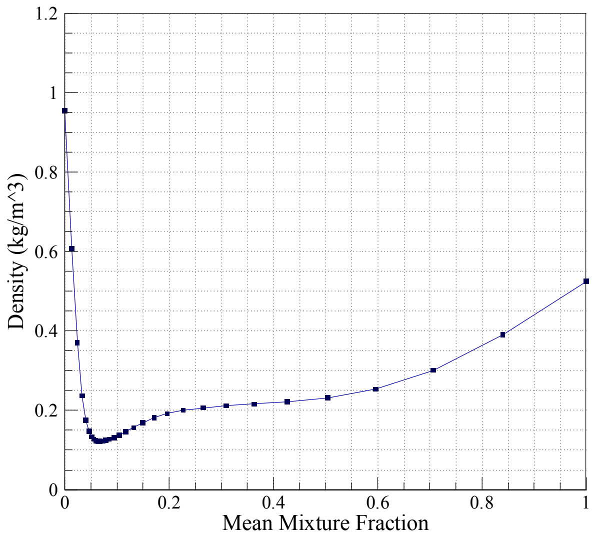

Figure 3 Mean density versus fuel mixture fraction

Indeed, the mixture fraction is the mass fraction of an element, which originates from the fuel stream. If a secondary stream, e.g., fuel, oxidizer, or non-reacting flow, is available there the mixture fraction of secondary flow or secondary fuel stream can be obtained from

$$f_{fuel} + f_{sec} + f_{ox} = 1 \qquad (2)$$

According to this equation, the summation of all chemical species, containing a reacting flow system, i.e., fuel, oxidizer, and secondary stream as illustrated in Fig. 4.

The relation between streams, given by Eq. (2), presents a triangular plane expression. The maximum value for this plane is one at all its vertices. In the space of mass fractions, those values which are located on triangle *ABC* would be valid. So, the two mixture fractions of f_{fuel} and f_{sec} are not independent from each other. Their values are given by Eq. (2).

The assumption of equal diffusivity coefficients is valid for all species in laminar flow cases. However, in turbulent flow cases, the transport phenomenon would be dominant in general. So, the implementation of this assumption for turbulent flow cases would be logic and acceptable.

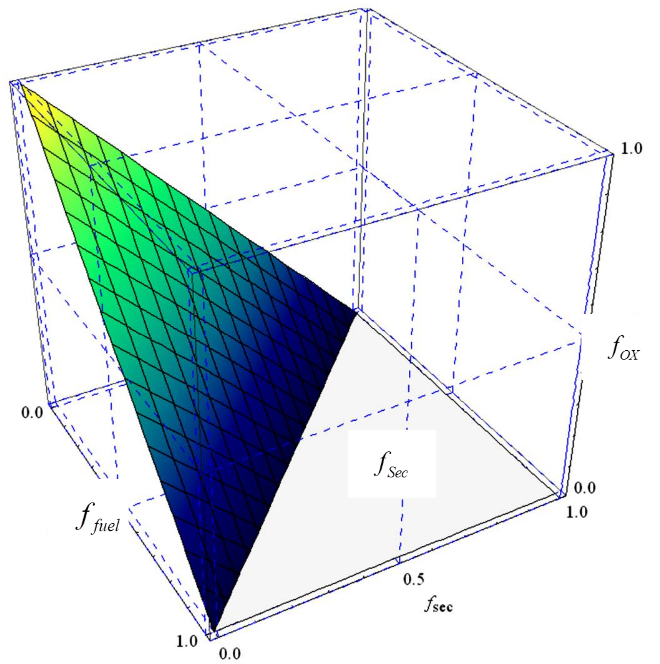

Figure 4 The relationship between f_{fuel}, f_{sec}, and f_{ox}.

Favre mean averaged equation for the mixture fraction is given by

$$\frac{\partial}{\partial t}\left(\rho \bar{f}\right) + \nabla.\left(\rho \vec{v} \bar{f}\right) = \nabla.\left(\frac{\mu_t}{\sigma_t} \nabla \bar{f}\right) + S_m \qquad (3)$$

The source term S_m includes the mass transfer rate from the gaseous phase. In order to close the turbulence-chemistry equations, the mixture fraction variance, $\overline{f'^2}$, is obtained from

$$\frac{\partial}{\partial t}\left(\rho\overline{f'^2}\right)+\nabla.\left(\rho\vec{v}\,\overline{f'^2}\right)=\nabla.\left(\frac{\mu_t}{\sigma_t}\nabla\overline{f'^2}\right)+C_g\mu_t\left(\nabla\bar{f}\right)^2-C_d\rho\frac{\varepsilon}{k}\overline{f'^2} \quad (4)$$

where $f'=f-\bar{f}$ and that the values of σ_t, C_g, and C_d are fixed at 0.85, 2.86, and 2.0, respectively. In general, the instantaneous state of fluid thermochemistry depends on the mixture fraction value. So, the other scalar quantities can be readily derived from the knowledge of mixture fraction without solving any transport equations for them.

Turbulence Model

We use the two-equation $k-\varepsilon$ turbulence model to perform our simulations [8, 14]. Comparing with other turbulence models, the reliability of achieved solutions and the high speed of convergence were two reasons to choose this model. As is known, the two parameters of k (the turbulence kinetic energy) and ε (the dissipation rate of turbulence fluctuations) can be derived from

$$\rho\left(\frac{\partial k}{\partial t}+\bar{u}.\nabla k\right)-\nabla.\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\nabla k\right]-\mu_t P+\rho\varepsilon=0 \quad (5)$$

$$\rho\left(\frac{\partial \varepsilon}{\partial t}+\bar{u}.\nabla \varepsilon\right)-\nabla.\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right]-C_{\varepsilon 1}\frac{\varepsilon}{k}\mu_t P+C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}=0 \quad (6)$$

where the constants are $C_\mu=0.09$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.0$, $C_{\varepsilon 1}=1.44$, and $C_{\varepsilon 2}=1.92$. Additionally, the turbulence production term is calculated from

$$P=\nabla\bar{u}:\left(\nabla\bar{u}+\nabla\bar{u}^T\right) \quad (7)$$

Wall Function Implementation

We use the standard wall function in the vicinity of walls. If we define $y^+=(\rho\delta/\mu)(\tau_w/\rho)^{1/2}$ and $u^+=u/(\tau_w/\rho)^{1/2}$, where the scalar velocity $u_\tau\equiv(\tau_w/\rho)^{1/2}$ can be obtained from [14]

$$u^+=y^+;\ y^+<30 \qquad \text{(in viscous sub-layer)} \quad (8)$$

$$u^+=\frac{1}{\kappa}\ln\left(Ey^+\right); \qquad \text{(in buffer layer)} \quad (9)$$

where $\kappa=0.41$ is the Von-Karman constant, and E is the roughness parameter, which is about 9.0 for smooth wall surface cases.

Conservation Equations

The continuity and momentum conservation equations are respectively given by

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x}=0 \quad (10)$$

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i u_j\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_i}\left((\mu+\mu_t)\left[\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right]\right)+\rho g_i\left(T-T_0\right) \quad (11)$$

where the last term on the right hand side of momentum conservation equation considers the important buoyancy effect, which shows up due to the temperature differences.

Mixing Parameter

We use the parameter σ (mixture fraction standard deviation) to analyse the mixing performance in our incinerator. It is defined as

$$\sigma=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(f_i-\bar{f}\right)^2} \quad (12)$$

where f_i is the mixture fraction at the ith cell, which is located in our target plane. This plane is perpendicular to the incinerator axis. Moreover, $\bar{f}$ is the mean mixture fraction of the cells co-located on one plane. N is the total number of mesh cells on one plane.

The governing equations are discretized using a second-order upwind method. We also use the SIMPLE algorithm to provide suitable pressure-velocity coupling.

SOLUTION DOMAIN AND GRID GENERATION

The current incinerator is illustrated in Figure 5. The incinerator has three input streams of air, waste-gas, and fuel-gas. The details of these streams are provided in Table 1. The pressure is about 82 kPa for all streams. As the outlet boundary conditions, we assume a total pressure of 82 kPa and temperature of 288.15 K at the incinerator inlets.

Table 1. The details of air, fuel, and waste-gas at the incinerator inlets.

Inlet	Temperature (K)	Mass Flow Rate (g/s)	Hydraulic Diameter (mm)	Components (Mole Fraction)				
Waste-Gas	338.15	2084	350	CH_4	C_2H_6	C_3H_8	H_2	N_2
				0.7	0.06	0.05	0.15	0.04
Fuel-gas	313.15	30	5*16 Nozzles	CH_4	CO_2	H_2O	O_2	N_2
				0.02	0.065	0.1	0.075	0.74
Air	298.15	917	500	O_2		N_2		
				0.21008		0.78992		

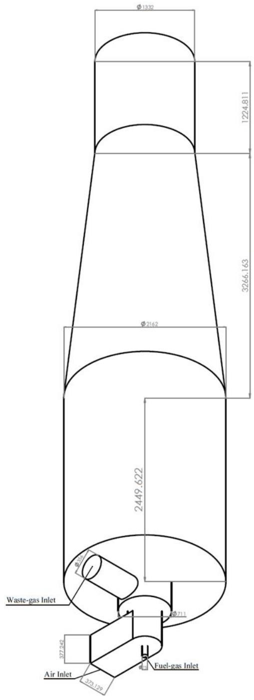

Figure 5 The primitive geometry of the waste-gas incinerator

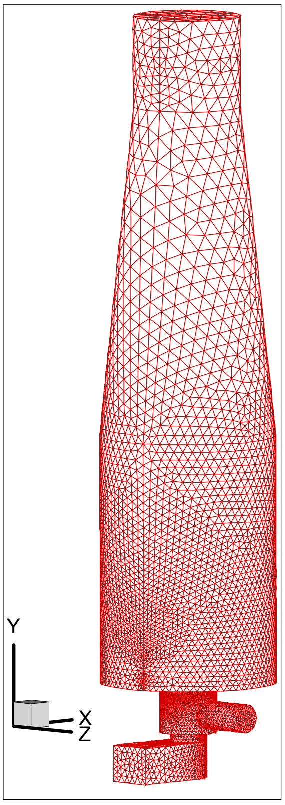

Figure 6 The complete incinerator with an unstructured grid distribution

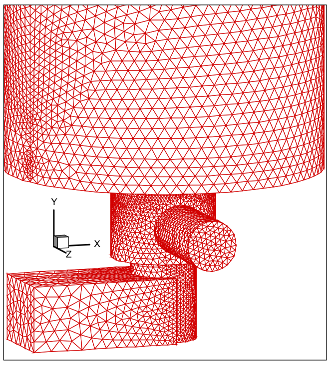

Figure 7 A close view of waste-gas and air inlets

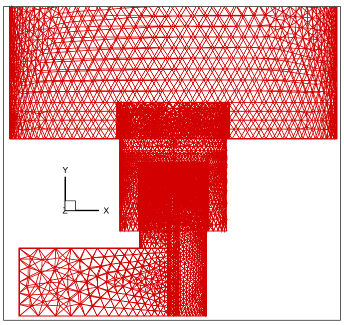

Figure 8 A close view of fuel and air inlets in X-Y plane

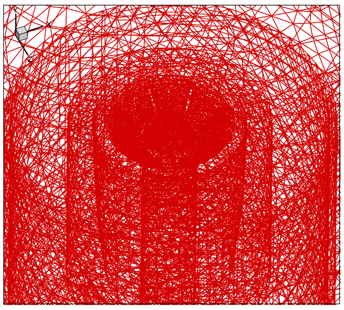

Figure 9 A close up view of furnace, burner

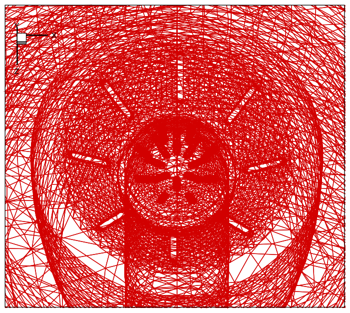

Figure 10 A close up view of furnace nozzles

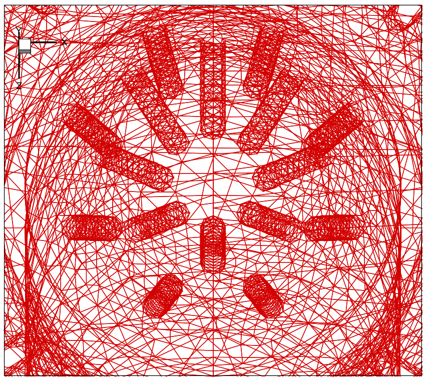

Figure 11 A close up view of furnace central nozzles

A 3D unstructured tetrahedral prism mesh was generated throughout the incinerator. Fine mesh was used for the nozzle exits and especially at the height where the flame appears. The total number of cells in this mesh is nearly 640,000. Figures 6-12 show more details about the mesh structure and its quality.

RESULTS AND DISCUSSIONS

As was elaborated before, one approach to minimize the pollution in a combustion chamber is to increase the mixing quality. Good mixing process can lead to longer residence time of species in the chamber and consequently a better oxidation of gaseous particles and less hazardous pollution. For example, an improper waste gas entrance can cause inappropriate vertical vortices, which in turn affect part of the reacting particles and may expose them to low temperature zones near the wall of incinerator, where the chance of oxidation reduces seriously. In other words, exposing the reacting mixture to low-temperatures may result in incomplete burnings. For example, the CO oxidation process would start when the combustion temperatures is sufficiently high, i.e., 800-900°C. The low-temperature zones are prone to produce carbon-monoxide formation. Changing the position of waste gas nozzle to somewhat at the upper level of the furnace bottom and inclining it with a 45 degrees upward angle, we would expect to earn some positive effects like, eliminating vertical vortices in the incinerator and promoting them to horizontal ones, which can simultaneously rotate around the incinerator axis. The results for the primitive incinerator configuration are observed in Figs. 12 and 13. Figure 12 shows the complete incinerator configuration. Also, Fig. 13 shows the streamline patterns for the waste gas entering into the incinerator. As is seen, the flow pattern exhibits fully asymmetric.

As was mentioned before, we intend to improve the mixing process in the primitive incinerator by replacing the waste-gas inflow from the bottom of furnace to somewhere right at the bottom part of furnace wall. As is seen in Fig. 15, the waste gas inlet from the bottom has been replaced with two inlets at the upper part of incinerator burner. These two inlets have an inclination angle of 45 degrees upward and 45 degrees counter-clockwise with the tangent lines on the furnace periphery. These two new inlets can have either circular or rectangular shapes. Figure 14 shows the waste-gas streamlines in the incinerator considering a rectangular cross-section for these two inlets as well as square.

A quantitative comparison among different waste gas inlet cross-sections are illustrated in Figs. 20 and 21 at several longitudinal planes through the incinerator. They imply that the mixing quality is a direct function of generated flow patterns. One may readily conclude that the waste-gas entrance through a rectangular cross section provide a better mixing throughout the incinerator axis. This means that, using the rectangular cross section for the waste-gas entrance to the incinerator it would result in a homogeneous mixing and desirable dilution zones.

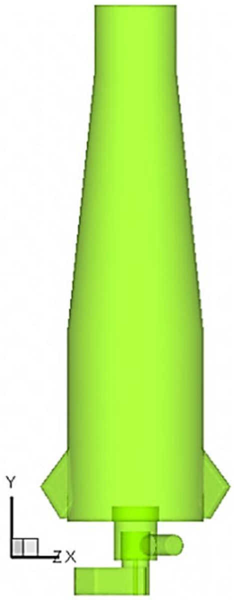

Figure 14 The modified incinerator with new position for the waste-gas inlets having rectangular cross-section and an upward inclination at angle of 45°

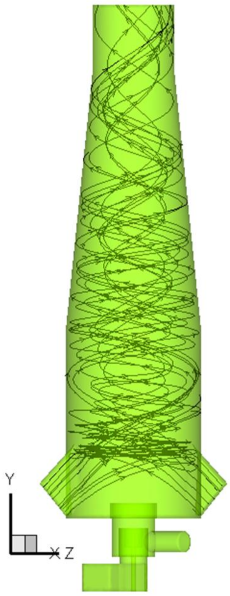

Figure 15 Waste-gas streamlines through the modified incinerator using two new inlet positions and directions having a rectangular cross-section shape

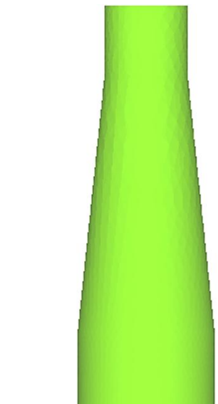

Figure 12 The primitive incinerator configuration

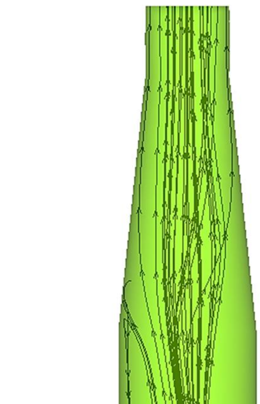

Figure 13 Waste-gas streamlines through the primitive incinerator

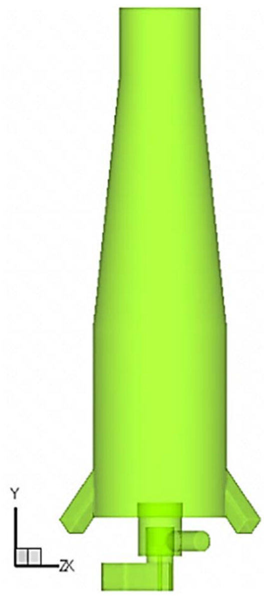

Figure 16 The modified incinerator with new position for the waste-gas inlets having square cross-section and an upward inclination at angle of 45°

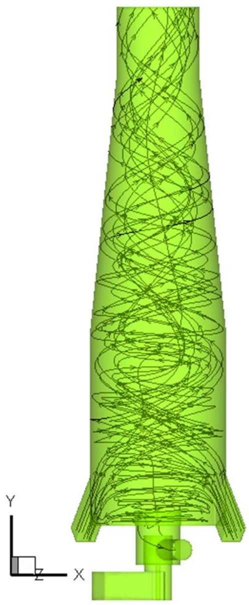

Figure 17 Waste-gas streamlines through the modified incinerator using two new inlet positions and directions having a square cross-section shape

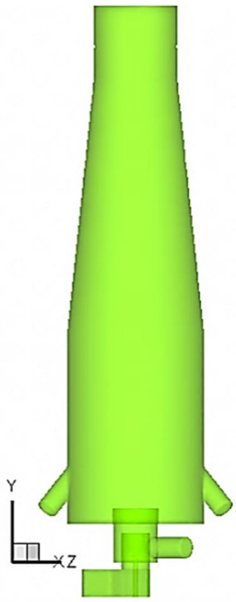

Figure 18 The modified incinerator with new position for the waste-gas inlets having circular cross-section and an upward inclination at angle of 45°

Figure 19 Waste gas streamlines through the modified incinerator using two new inlet positions and directions having a circular cross-section shape.

Unfortunately, the standard deviation parameter does not give any explicit information about the species residence time. We know that the residence time information could provide useful data about the efficiency of our new designed waste-gas inlets. To enrich our study, we calculate the species residence time in the incinerator using the Lagrangian particle tracking method, see Fig. 22. This figure shows that the use of rectangular and circular cross-sections would be more preferable than the square one for the waste-gas entrance nozzle configuration. To reach a suitable conclusion, we take into account the mixing quality and standard deviation of species as well as the residence time for the species passing through the incinerator to determine the best new waste-gas inlet choice. Our comparisons show that the first priority should be given to the one with a circular cross-section. The next priority is the square shape and the last is the rectangular one. Naturally, a better priority choice would automatically result in a better combustion process in the incinerator resulting a more complete oxidation and less ambient pollution.

CONCLUSION

We used the computational fluid dynamics tool and studied the flow in an incinerator. To improve the mixing quality in the incinerator, we presented three new waste-gas inlet designs with circular, square, and rectangular cross-sections entering into the incinerator tangentially and upward. They are located above the bottom face of furnace. We showed that the cross-section of waste-gas entering into the incinerator would have important effect on the flow mixing quality and the residence time for each species. It can be deduced that the rectangular cross-section would improve the mixing very effectively especially near the incinerator burner. This configuration of inlet streams can cause homogeneous combustion chamber which fuel stream particles are propagated uniformly throughout the incinerator. On the other hand, the circular cross-section design would increase the species residence time considerably in the incinerator. Evidently, the new designs would prevent a continuous impingement of waste-gas particles to the furnace wall, and which can effectively reduce the maintenance costs. Our study shows that the change of original waste-gas entrance, which is from the bottom of burner and along the axis of incinerator, to two separated ones, which enter from the bottom of furnace wall with tangential and upward direction, will improve both the mixing quality and the species residence time. However, among different waste-gas inlet cross-sections, the one with circular cross-section would perform much better than the square and rectangular ones, especially for this incinerator with high CO concentrations at the outlet of the furnace. For furnaces with high NO_X pollutions or even with high operating temperatures, the rectangular cross-section configuration is recommended for providing more homogeneous mixing and dilution zones.

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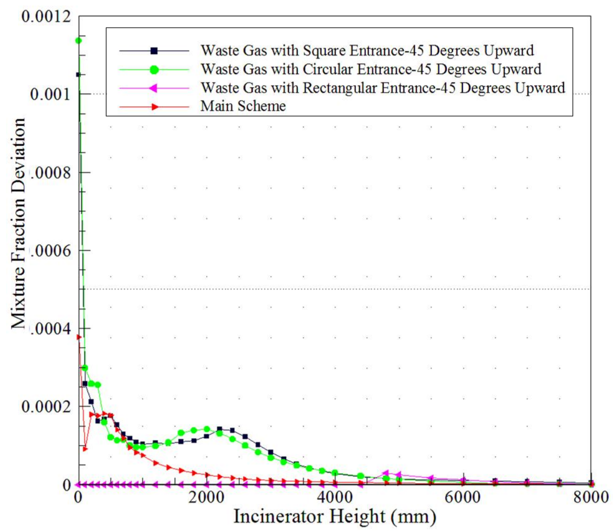

Figure 20 Standard deviation for the distribution of chemical species along the incinerator axis

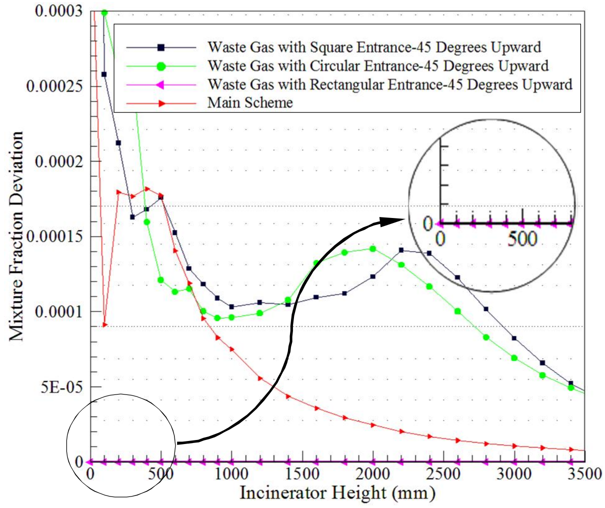

Figure 21 Standard deviation of the mixture fraction versus the height of incinerator magnifying the distance from the bed up to a height of 3500 mm

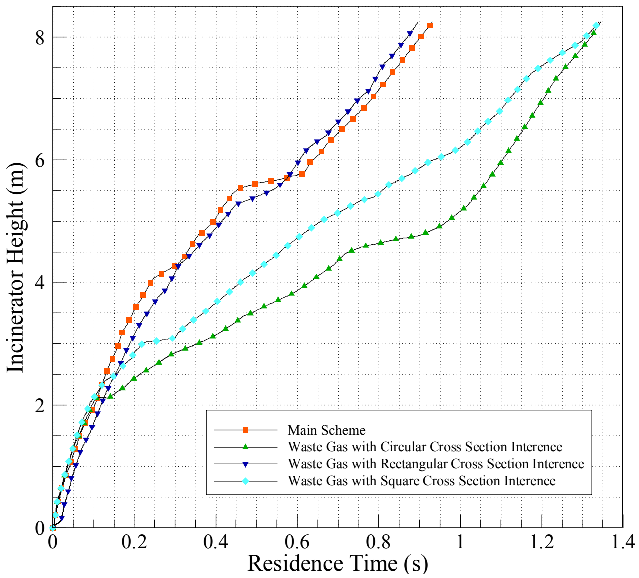

Figure 22 Residence time of chemical species along the incinerator height

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